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(71) Applicant (*for all designated States except US*): **PATHFINDER ENERGY SERVICES LIMITED** [GB/GB]; 1 Howe Moss Drive, Kirkhill Industrial Estate, Dyce, Aberdeen AB21 0GL (GB).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): **MCELHINNEY, Graham, Arthur** [GB/GB]; 44 High Street, Inverurie, Aberdeenshire AB51 3XS (GB).

(74) Agent: **ROBERTS, Peter, David**; Marks & Clerk, 83-85 Mosley Street, Sussex House, Manchester M2 3LG (GB).

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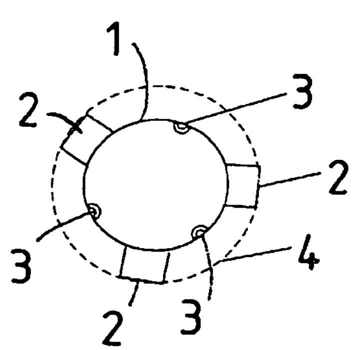
(54) Title: BOREHOLE SHAPE DETERMINATION



(57) Abstract: A borehole attribute determination apparatus comprising at least three sensors mounted on a drill head, each sensor being arranged to determine a distance from the sensor to an adjacent side of the borehole. Preferably sensors are acoustic transducers, which perform caliper measurments at two separate distances from the drillhead, which can subsequently be compared to monitor change in borhole size and shape.

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BOREHOLE SHAPE DETERMINATION

The present invention relates to a method and apparatus for determining attributes of a borehole.

During and after the drilling of a borehole it may be important to know the size and shape of the borehole. This information can be used in analysing stresses around the borehole, determining the location of problem formations around the borehole, for example swelling clays, and monitoring the behaviour of the problem formations.

In many instances it may be advantageous to determine the size and shape of a borehole while the borehole is being drilled. However, the environment near the bottom of the borehole during drilling is particularly hostile, and there is currently no known way to monitor the size and shape of a borehole while it is being drilled.

It is an object of the present invention to provide a novel method of determining borehole characteristics.

According to a first aspect of the invention there is provided a borehole attribute determination apparatus comprising at least three sensors mounted on a drill, each sensor being arranged to determine a distance from the sensor to an adjacent side of the borehole.

Preferably the sensors are mounted on the drill head. The use of the term drill head is not intended to limit the location of the sensors so as to be immediately adjacent a cutting tool part of the drill. Instead, it will be understood that the sensors may be located some distance away from the cutting tool part of the drill.

Preferably, the apparatus further comprises processing means arranged to determine an estimated cross-sectional size and shape for the borehole based upon the distances determined by the sensors.

Preferably, the processing means is arranged to use a predetermined estimate of the cross-sectional size of the borehole to determine the estimated cross-sectional size and shape for the borehole.

Preferably, the sensors are acoustic transducers.

Preferably, the apparatus includes means for sending data from the drill head to the surface whilst the drill head remains in the borehole.

The invention is advantageous because it allows information regarding the size and shape of the borehole to be sent to at a very low bit rate of transmission. The bit rate is sufficiently low that the information may be sent as 'measurement while drilling' data.

Preferably, the data sending means comprises a valve located in the drill head and arranged to send the data as pressure waves generated by opening and shutting the valve.

Preferably, additional sensors are provided adjacent the at least three sensors, the additional sensors providing complementary information regarding the borehole.

Preferably, the complementary information is stored within the drill head.

Preferably, the apparatus further comprises processing means arranged to combine the complementary information and the estimated cross-sectional size and shape to provide refined estimated characteristics of the borehole.

Preferably, the processing means comprises a neural network.

Preferably, the apparatus is arranged to obtain six or more distance measurements for a given cross sectional location.

Preferably, at least three of the measurements are made using three sensors, and three subsequent measurements are made using the same three sensors.

Preferably, the apparatus is provided with six sensors arranged to obtain six different distance measurements for a given cross sectional location.

Preferably, the processing means is arranged to use interpolation to refine an estimate of the size and shape of the borehole, or to estimate variation of the size and shape of the borehole between adjacent measurements.

Preferably, each transducer is arranged to emit a pulse, and the thickness of mud cake located at sides of the borehole is determined by monitoring a first received pulse which is reflected from the mud cake and a second received pulse which is reflected from rock located beyond the mud cake.

Preferably, the processing means is arranged to compare estimates of the shape and size of the borehole at a given location which are determined more than once at different time intervals, to allow variation of the shape and size over time to be measured.

Preferably, at least three sensors are provided close to the drill head, and a further at least three sensors are located at a known separation further from the drill head, thereby allowing distance moved by the drill head to be determined by comparing the estimated borehole size and shape that is monitored by the separated sensors.

According to a second aspect of the invention there is provided a method of determining borehole characteristics comprising deploying a least three sensors within the borehole, each sensor being arranged to determine a distance from the sensor to an adjacent side of the borehole, and determining an estimated cross-sectional size and shape for the borehole based upon a predetermined estimate of the size of the borehole.

Preferably the sensors are acoustic transducers. Any other suitable sensor may be used.

Preferably, data is sent from the borehole to the surface whilst the sensors remain in situ.

Preferably, the data is sent as pressure waves by opening and shutting a valve located in the borehole.

The invention is advantageous because it allows information regarding the size and shape of the borehole to be sent to at a very low bit rate of transmission. The bit rate is sufficiently low that the information may be sent as 'measurement while drilling' data.

Suitably, additional sensors are provided adjacent the at least three sensors, the additional sensors providing complementary information regarding the borehole.

Preferably, the complementary information is stored in a memory within the borehole, the memory subsequently being removed from the borehole in order to access the memory.

A specific embodiment of the invention will now be described by way of example only with reference to the accompanying figures, in which:
Figure 1 is a schematic illustration of a drill head which embodies the invention;
Figures 2 to 5 are schematic illustrations of boreholes; and
Figure 6 is a illustration of a three-dimensional measurement of a borehole made using the embodiment of the invention.

Referring to figure 1, a drill-head which embodies the invention comprises a cylindrical housing 1 onto which are mounted three stand-off blades 2 and three ultrasonic transducers 3. The transducers are embedded in the drill-head housing 1 to protect them from the harsh environment of the borehole.

The drill-head is configured to cut a circular hole under ideal drilling conditions. The circumference of the circular hole that would be cut by the drill head, referred to hereafter as the minimum circle, is shown as a broken line 4 in figure 1.

Each ultrasonic transducer 3 is used to measure the distance from the transducer to the wall of the borehole by emitting an ultrasonic pulse and measuring the time elapsed until the pulse is reflected back to the transducer.

The measured distances are transmitted from the drill head to the surface by opening and shutting a valve located at or adjacent the drill head, the valve being arranged to generate pressure waves which travel along the body of the drill to the surface. Transmission of data to the surface using this method is known in the art. Such transmission typically operates at a data rate of between 1 and 5 bits per second.

In prior art arrangements the data transmitted to the surface may comprise a measurement of the rotation of the drill head. The invention is advantageous because in addition to this measurement, it also allows measurement of the distance of the borehole from the drill head in three directions. The extra amount of data to be transmitted is sufficiently small that it does not exceed the bit rate of the pressure wave based data transmission. The distance data is processed at the surface, for example using a personal computer, to determine the shape of the borehole.

The distances measured by the transducers 3 are shown in figure 2. The distances are labelled a, b and c for ease of reference. The borehole 5 shown in figure 2 is much bigger than the minimum circle 4, and is elliptical in shape. The distances a, b and c measured by the transducers are used to determine the shape of the borehole.

The shape of the borehole could be determined from the three distance measurements a, b and c by using simple interpolation. However, interpolation in this manner introduces an error since the longest measured distance, in this case a, will always be interpreted as being the long axis of an ellipse. This is shown on Figure 3, where it can be seen that the interpolated borehole shape 6 does not coincide with the actual borehole 5. The embodiment of the invention overcomes this problem using a geometrical calculation.

The geometrical calculation may be understood by firstly considering a circular borehole. Referring to figures 1 and 2, if the drill head 1 is placed anywhere within a

circular borehole the vector sum of the three measurements a, b and c will be constant.

$$k = \text{Sqrt}\,(a^2 + b^2 + c^2) \qquad \text{Equation 1}$$

The diameter of the borehole may be determined by multiplying k by 1.155 (this is equivalent to diameter = k / sin (60)).

In a numerical example the three measurements may all be equal at 6.93 arbitrary units, giving a value of k = 12. Multiplying by 1.155 provides the diameter of the borehole = 13.86.

If the borehole is a simple ellipse, as shown in Fig 3, then the vector sum of the three measurements a, b and c is greater. The shape of the borehole is derived using the three measurements a, b and c, together with the constant k which has previously been determined. The constant k is determined on the basis of the size of a circular borehole that it is estimated would be drilled under the known conditions. The shape of the borehole is determined using simultaneous equations which determine which measurement includes the greatest asymmetry. First, an asymmetry value is estimated for each measurement:

$$a' = a - (\text{sqrt}\,(k^2 - (b^2 + c^2))) \qquad \text{Equation 2}$$

$$b' = b - \text{sqrt}\,(k^2 - (a^2 + c^2)) \qquad \text{Equation 3}$$

$$c' = c - \text{sqrt}\,(k^2 - (a^2 + b^2)) \qquad \text{Equation 4}$$

The asymmetry value is then subtracted from the measured value to provide an estimated corrected value, and the corrected value is checked to see whether, together with the measured values, it would yield a circle:

$$a'a' = k - \text{sqrt}\,(b^2 + c^2 + (a - a')^2) \qquad \text{Equation 5}$$

$$b'b' = k - \text{sqrt}\,(c^2 + a^2 + (b - b')^2) \qquad \text{Equation 6}$$

$$c'c' = k - \text{sqrt}\,(a^2 + b^2 + (c - c')^2) \qquad \text{Equation 7}$$

The estimated corrected value is deemed to have been found if one of equations 5-7 yields a zero result. For example if equation 7 yields a zero result then this indicates that the estimated corrected value (c-c') has been correctly determined. This indicates that the value c introduced asymmetry into the measured borehole, and the value c' is a measurement of the asymmetry that was introduced.

A numerical worked example of equations 2 to 7 is as follows:

2.18631	=	$6.333 - \mathrm{sqrt}\,(12 - (6.25^2 + 11.05^2))$	Equation 2
1.97842	=	$6.25 - \mathrm{sqrt}\,(12 - (6.333^2 + 11.05^2))$	Equation 3
3	=	$11.05 - \mathrm{sqrt}\,(12^2 - (6.333^2 + 11.05^2))$	Equation 4
3.28994	=	$12 - \mathrm{sqrt}\,(6.25^2 + 11.05148^2 + (6.333\text{-}2.18631^2))$	Equation 5
3.16421	=	$12 - \mathrm{sqrt}\,(11.05148^2 + 6.333^2 + (6.25\text{-}1.97842)^2)$	Equation 6
0	=	$12 - \mathrm{sqrt}\,(6.3333^2 + 6.25^2 + (11.05148\text{-}3)^2)$	Equation 7

In equation 7, the value c'c' = zero indicates that a, b and (c-c') are measurements of a circle. This indicates that equations 4 and 7 have determined the extra length of c which caused asymmetry of the borehole. In this instance the extra length of c is 3 arbitrary units.

In a circular borehole all three results give the same value and if the borehole is of the dimension specified then the results approximate to zero for a', b',c', a'a', b'b', c'c'.

Using the estimated value k is advantageous because it allows a reasonably good determination of the shape of the borehole to be determined whilst requiring the transmission of only a small amount of data to the surface.

Three transducers is considered to be the minimum number required to provide useful information regarding the shape of the borehole. It will be appreciated that more information regarding the shape of a borehole may be obtained by providing more than three transducers on the drill head housing. The transducers may be arranged about the housing in a single ring.

Multiple determinations of distances for a borehole region of interest may be obtained by passing the transducers over the region of interest several times, i.e. moving the drill-head back and forth through the region of interest. This is often done during the making of connections, reaming and hole cleaning, new runs etc. The multiple readings would not provide any additional information if they simply measured the same distances twice. However, in practice there will usually have been some rotation or movement of the transducers, due to movement of the drill, between successive measurements, and so the distances measured are different.

Multiple determinations may be obtained using several sets of transducers spaced out along the housing. Using six transducers at once is equivalent to rotating once between two readings taken using three transducers. The result is six transducer distance measurements in different directions, for example as shown in figure 4. The six distance measurements allow the direction and magnitude of the major axis of the ellipse to be determined with greater certainty.

If we consider that two sets of readings which are taken 2 seconds apart are from the same depth then any rotation around the long (z) axis will give three extra readings. These can be used to determine the direction of the long axis of an ellipse. They also allow the asymmetry to be solved in a different way from before.

More readings can be taken and used this way. However, if the rate of change of the borehole shape is greater than the sample interval then errors may be introduced.

In figure 5 the rate of change of the distance measurements a to a', b to b' and c to c' is dependent on their positions with respect to the long axis of the ellipse. The distance, a to a' increasing (+) rapidly will indicate that it is closer to the long axis of the ellipse, whilst b to b' is decreasing slowly and is moving away from the long axis. The position (rotation) of the long axis and its length may be derived from the measurement of a.a',b,b',c and c'.

There are various standard methods for interpolation that may be used to determine the shape of an elliptical borehole, for example the method described above. It is preferred in many methods to determine the length and direction (rotation) of the long

axis of the ellipse, and then use this as a starting point for the interpolation. The embodiment of the invention may be used to determine the length and direction (rotation) of the long axis of the ellipse by for example taking multiple measurements as described above.

Interpolation may be applied along the long axis of the borehole, i.e. to generate a three-dimensional representation of the borehole. A three-dimensional representation of the borehole may be generated and displayed to an operator as the borehole is being drilled.

The shape of a borehole is governed by the mechanical/chemical properties of the rock into which the borehole is drilled, the mechanics of the drill bit, the properties of the drilling fluid and the deviations in the path of the well bore. Properties that may be measured by sensors mounted on the drill head include density, porosity, gamma ray, sonic-velocity, shear wave, resistivity, nuclear magnetic resonance data, weight on bit, rpm of the drill string, drilling fluid properties, etc. Information about these properties may be used to assist in the analysis of the shape of the borehole. For example, from a 'logging whilst drilling' (LWD) tool it may be possible to derive information on the physical and chemical properties of the rock, from the mud analysis the drilling fluid properties can be determined. The rate of penetration, weight on bit, rpm and torque can be measured. This data is not sent to the surface using the pressure wave method, since the amount of data generated significantly exceeds the available bandwidth. Instead, the data is stored and is read when the drill head returns to the surface. The data may be used to assist in the analysis of the shape of the borehole

If the formation was a homogenous firm sandstone one may expect the borehole to be circular and similar in radius to the drill bit. If the formation was a friable an isotropic clay stone, drilled with under balanced mud. The borehole maybe expected to be elliptical along the major axis of stress within the clay stone.

There are many parameters involved and the best way to account for their influence is to use a trained neural net with fuzzy logic. In this way the complex interrelationships

can be used to give a resultant shape from a minimum of distance data. For filling the criteria of minimum transmission with maximum image definition.

The ultrasound used for the measurement of distance can also be used to determine the thickness of the mud cake. This cake is caused by the loss of fluid to the rock formation surrounding the borehole. When the fluid is lost the surface of the rock acts as a filter and particles build up on its surface. If the formation (rock) is very permeable then the build up can happen quickly and the cake can be thick. The acoustic wave will reflect of both the surface of the mud cake and the rock surface. The difference between these two measurements is the thickness of the mud cake. This information may be very useful when analysing a fluid reservoir. Information about the permeability is of prime importance for maximising oil and gas production. The analysis of the returned acoustic wave can be carried out within the down hole tool and the results sent to the surface as mud cake thickness.

Changes in the shape of the borehole over time can be caused by slow swelling clays, washing out of the formations by the borehole fluid, abrasion by stabilisers and other drill string components etc. These can be analysed at any time by repeating measurement over the section of interest within the borehole. This provides an extra dimension to the shape of the borehole i.e. how it changes with time.

An example of a 3D view generated using the invention is shown in figure 6.

Due to the elastic nature of the drill string (i.e. the connections between the drill head and the surface) measurements of distance travelled from surface frequently contain errors. The embodiment of the invention may be used to measure distance travelled with improved accuracy. This may be done by locating two sets of acoustic transducers at a known separation (for example 100 feet) along a pipe, close to the drill head. A shape feature of the bore will be monitored by the first set of transducers and communicated to the surface. Subsequently, the same shape feature will be monitored by the second set of transducers, indicating that the drill head has travelled the distance of the known transducer separation (100 feet in this example). Continuous monitoring allows the distance travelled to be continually derived.

An advantage of the invention is that it allows the direction of stress within a reservoir to be determined using logs and images. This information can be useful when determining well placement for recovery and well drill ability.

The depth of the drill head from the surface may be determined using a known standard measurement which is performed from the surface.

The embodiment of the invention may use a standard DNSC tool. Software used may be EXCELl macros, AUTOCAD 2000, 3D STUDIO MAX 3.

CLAIMS

1. A borehole attribute determination apparatus comprising at least three sensors mounted on a drill, each sensor being arranged to determine a distance from the sensor to an adjacent side of the borehole.

2. A borehole attribute determination apparatus according to claim 1, wherein the sensors are mounted on a drill head of the drill.

3. A borehole attribute determination apparatus according to claim 1 or claim 2, the apparatus further comprising processing means arranged to determine an estimated cross-sectional size and shape for the borehole based upon the distances determined by the sensors.

4. A borehole attribute determination apparatus according to any preceding claim, wherein the processing means is arranged to use a predetermined estimate of the cross-sectional size of the borehole to determine the estimated cross-sectional size and shape for the borehole.

5. A borehole attribute determination apparatus according to any preceding claim, wherein the sensors are acoustic transducers.

6. A borehole attribute determination apparatus according to any preceding claim, wherein the apparatus includes means for sending data from the drill head to the surface whilst the drill head remains in the borehole.

7. A borehole attribute determination apparatus according to claim 6, wherein the data sending means comprises a valve located in the drill head and arranged to send the data as pressure waves generated by opening and shutting the valve.

8. A borehole attribute determination apparatus according to any preceding claim, wherein additional sensors are provided adjacent the at least three sensors, the additional sensors providing complementary information regarding the borehole.

9. A borehole attribute determination apparatus according to claim 8, wherein the complementary information is stored within the drill head.

10. A borehole attribute determination apparatus according to claim 8 or claim 9, wherein the apparatus further comprises processing means arranged to combine the complementary information and the estimated cross-sectional size and shape to provide refined estimated characteristics of the borehole.

11. A borehole attribute determination apparatus according to claim 10, wherein the processing means comprises a neural network.

12. A borehole attribute determination apparatus according to any preceding claim, wherein the apparatus is arranged to obtain six or more distance measurements for a given cross sectional location.

13. A borehole attribute determination apparatus according to claim 12, wherein at least three of the measurements are made using three sensors, and three subsequent measurements are made using the same three sensors.

14. A borehole attribute determination apparatus according to claim 12, wherein the apparatus is provided with six sensors arranged to obtain six different distance measurements for a given cross sectional location.

15. A borehole attribute determination apparatus according to any preceding claim, wherein the processing means is arranged to use interpolation to refine an estimate of the size and shape of the borehole, or to estimate variation of the size and shape of the borehole between adjacent measurements.

16. A borehole attribute determination apparatus according to claim 5 or any claim dependent thereon, wherein each transducer is arranged to emit a pulse, and the thickness of mud cake located at sides of the borehole is determined by monitoring a first received pulse which is reflected from the mud cake and a second received pulse which is reflected from rock located beyond the mud cake.

17. A borehole attribute determination apparatus according to any preceding claim, wherein the processing means is arranged to compare estimates of the shape and size of the borehole at a given location which are determined more than once at different time intervals, to allow variation of the shape and size over time to be measured.

18. A borehole attribute determination apparatus according to any preceding claim, wherein at least three sensors are provided close to the drill head, and a further at least three sensors are located at a known separation further from the drill head, thereby allowing distance moved by the drill head to be determined by comparing the estimated borehole size and shape that is monitored by the separated sensors.

19. A method of determining borehole characteristics comprising deploying at least three sensors within the borehole, each sensor being arranged to determine a distance from the sensor to an adjacent side of the borehole, and determining an estimated cross-sectional size and shape for the borehole based upon a predetermined estimate of the size of the borehole.

20. A method according to claim 19, wherein the sensors are acoustic transducers.

21. A method according to claim 19 or claim 20, wherein data is sent from the borehole to the surface whilst the sensors remain in the borehole.

22. A method according to claim 21, wherein the data is sent as pressure waves by opening and shutting a valve located in the borehole.

23. A method according to any preceding claim, wherein additional sensors are provided adjacent the at least three sensors, the additional sensors providing complementary information regarding the borehole..

24. A method according to claim 23, wherein the complementary information is stored in a memory within the borehole, the memory subsequently being removed from the borehole in order to access the memory.

25. A method according to claim 23 or claim 24, wherein complementary information and the estimated cross-sectional size and shape are combined to provide refined characteristics of the borehole.

26. A method according to claim 25, wherein the combination is carried out using a neural network.

27. A method according to any preceding claim, wherein at least six distance measurements are made for a given cross sectional location, and the results of the measurements are used to make a refined estimate of the size and shape of the borehole.

28. A method according to claim 27, wherein at least three of the measurements are made using three sensors, and three subsequent measurements are made using the same three sensors.

29. A method according to any preceding claim, wherein interpolation is used to refine an estimate of the size and shape of the borehole, or to estimate variation of the size and shape of the borehole between adjacent measurements.

30. A method according to claim 20 and any claim dependent thereon, wherein the thickness of mud cake located at sides of the borehole is determined by monitoring a first received pulse which is reflected from the mud cake and a second received pulse which is reflected from rock located beyond the mud cake.

31. A method according to any preceding claim, wherein the estimate of the shape and size of the borehole at a given location is determined more than once, at different time intervals to allow variation of the shape and size over time to be measured.

32. A method according to any preceding claim, wherein at least three sensors are provided close to the drill head, and a further at least three sensors are located at a known separation further from the drill head, thereby allowing distance moved by the drill head to be determined by comparing the estimated borehole size and shape that is monitored by the separated sensors.

33. A method of determining borehole characteristics substantially as hereinbefore described with reference to the accompanying figures.

34. A borehole attribute determination apparatus substantially as hereinbefore described with reference to the accompanying figures.

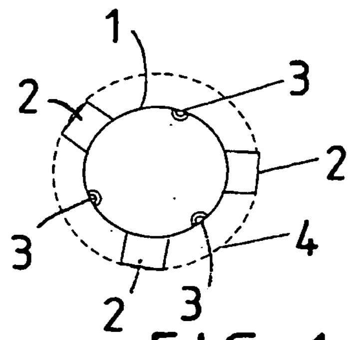

FIG.1

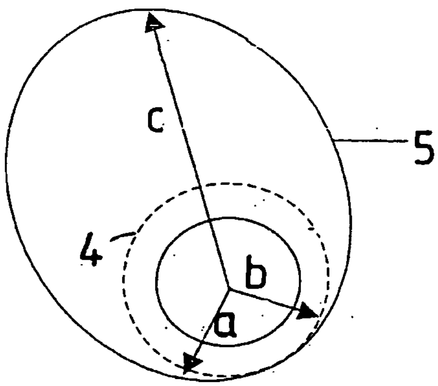

FIG.2

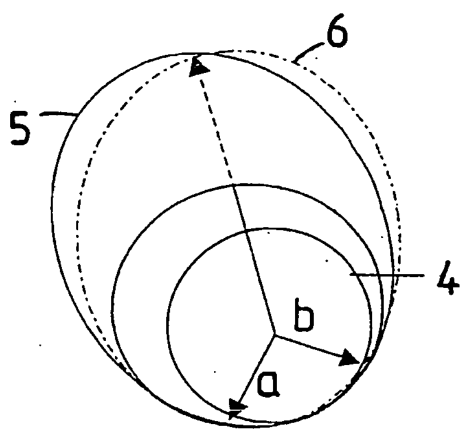

FIG.3

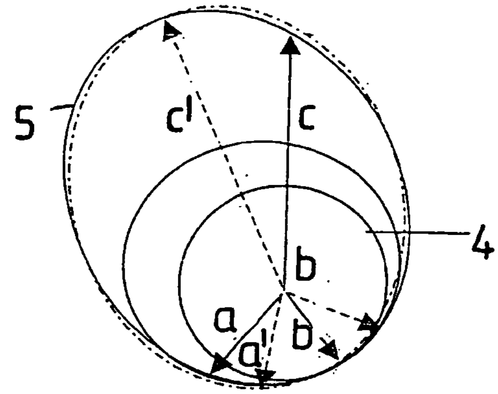

FIG.4

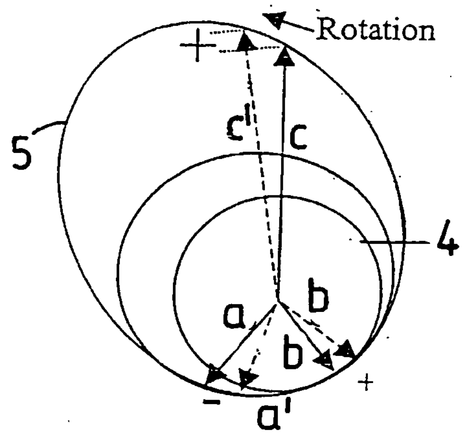

FIG.5

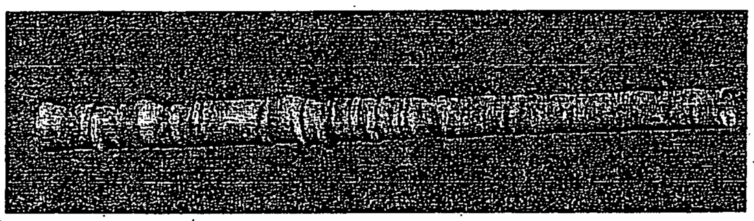

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 02/00790

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 E21B47/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 065 219 A (VARSAMIS GEORGIOS L ET AL) 23 May 2000 (2000-05-23)	1-13,15, 19-26, 28,29, 33,34
Y	the whole document	14, 16-18, 27,30-32
X	GB 2 328 746 A (DRESSER IND) 3 March 1999 (1999-03-03) page 8, line 30 page 12, line 22 -page 14, line 2; figures 1-3,8,9 page 17, line 1 -page 20, line 7	1-13,15, 19-26, 28,29, 33,34

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2002	03/06/2002

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European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	van Berlo, A

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